Black Hole Emergence in Supernovae

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Abstract. If a black hole formed in a core-collapse supernova is accreting material from the base of the envelope, the accretion luminosity could be observable in the supernova light curve. We present results of a fully relativistic numerical investigation of the fallback of matter onto a black hole in a supernova and examine conditions which would be favorable for detection of the black hole. In general, heating by radioactive decays is likely to prevent practical detection of the black hole, but we show that low energy explosions of more massive stars may provide an important exception. We emphasize the particular case of SN1997D in NGC1536, for which we predict that the presence of a black hole could be inferred observationally within the next year.

INTRODUCTION

Theory suggests that the compact object formed in a core-collapse supernova can be either a neutron star or a black hole, depending on the character of the progenitor and the details of the explosion [1]. The presence of several radio pulsars in sites of known supernovae provides substantial observational evidence that neutron stars are indeed created in supernovae, but similar evidence for a black hole - supernova connection is still mostly unavailable (see [2] for recent indirect evidence).

A newly formed black hole in a supernova can be identified directly if it imposes an observable effect on the continuous emission of light that follows the explosion - the *light curve*. In particular, if some material from the bottom of the expanding envelope remains gravitationally bound to the black hole, it will gradually fall back onto it, generating an accretion luminosity [3]. The black hole can be said to "emerge" in the supernova light curve if and when this luminosity becomes comparable to the other sources that power the light curve.

BLACK HOLE EMERGENCE IN THE LIGHT CURVE

Since the material which remains bound to the black hole following a supernova is outflowing in an overall expansion, the accretion rate must decrease in time. The expansion will also cause pressure forces to become unimportant eventually, and the

accretion will proceed as dust-like, following a power-law decline in time according to $\dot{M} \propto t^{-5/3}$ [4]. As shown in [3], the accretion flow and the radiation field proceed as a sequence quasi-steady-states, and the accretion luminosity can therefore be estimated according to the formula of Blondin [5] for stationary, spherical, hypercritical accretion onto a black hole ($L \propto \dot{M}^{5/6}$). The accretion luminosity then takes the form [3,6,7]:

$$L_{acc}(t) \propto L_{acc,0} t^{-25/18} \ , \tag{1}$$

where $L_{acc,0}$ depends on the kinetic energy, density and composition of the accreting material at the onset of dust-like flow.

Heating by decays of radioactive elements synthesized in the explosion may provide a significant source of luminosity in the late-time light curve. The time dependence of radioactive heating rate for an isotope X may be estimated as [8]

$$Q_X(t) = M_X \varepsilon_X f_{X,\gamma}(t) \mathrm{e}^{-t/\tau_X} \ , \tag{2}$$

where M_X is the total mass of the isotope X in the envelope, τ_X is the isotope's life time, and ε_X is the initial energy generation rate per unit mass. The factor $f_{X,\gamma}(t)$ reflects that not all $\gamma-$rays emitted in the decays are efficiently trapped in the envelope (and so do not contribute to the UVOIR luminosity).

Since accretion luminosity decreases as a power law in time while radioactive heating declines exponentially, then - assuming that spherical accretion persists - the accretion luminosity must eventually become the dominant source in the light curve. Furthermore, the non-exponential character of the accretion luminosity should be readily distinguishable in observations, announcing that the black hole has "emerged" in the light curve.

REALISTIC SUPERNOVAE

The typical amount of radioactive elements observed in type II supernovae suggests that an observation of black hole emergence in the light curve will usually be impractical. For example, luminosity due to accretion onto a hypothetical black hole in SN1987A would become comparable to the heating rate due to positron emission in ^{44}Ti decays only $\sim$900 years after the explosion. At this time the luminosity will have dropped to only $\sim 10^{32}$ ergs s^{-1} [3].

An important exception is expected in the case of higher mass progenitors, $M_* = 25 - 40 \ M_\odot$. Explosions of such stars are likely to involve significant early fallback even while the explosion is still proceeding. The survey of Woosley and Weaver [9] suggests that, in general, larger mass stars leave behind larger remnants and expel a smaller amount of radioactive isotopes (since these are synthesized in the deepest layers of the envelope, and a significant fraction is advected back onto the collapsed core). Clearly, for such an explosion, there is likely to be a larger reservoir of bound material for late time accretion, so that combined with the low background of radioactive isotopes, an actual detection of black hole emergence may become feasible.

We have recently conducted a numerical investigation of the expected emergence of a black hole in such supernovae [7]. This investigation was carried out with the spherical, fully relativistic radiation-hydrodynamics code described in [3], modified to include a variable chemical composition with a detailed photon opacity table, and to account for radioactive heating.

Black Hole Emergence in "Radioactive-Free" Supernovae

The most favorable case for identifying black hole emergence in supernova would be a low-to-medium energy ($\leq 1.3 \times 10^{51}$ ergs) explosion of a progenitor star with a mass of $35 - 40\ M_{\odot}$, where the ejected envelope is expected to be practically free of radioactive isotopes [9]. For such supernovae, the black hole should emerge within a few tens of days after the explosion. As an example, we show in Fig. 1 the calculated light curve of such an explosion, based on the theoretical model S35A of [9] ($M_{*}=35\ M_{\odot}$, $M_{BH}=7.5\ M_{\odot}$). The luminosity at emergence is $\gtrsim 10^{37}$ ergs s^{-1}, after which the light curve clearly follows a power law decline in time. If such a supernova were observed, it would offer an explicit opportunity to confirm the presence of a newly formed black hole [3].

SN1997D

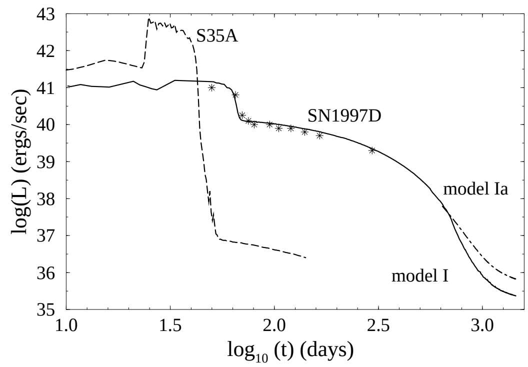
While such an ideal candidate is not available at present, SN1997D may provide a marginally *observable* case for idenfying the emergence of a black hole. Discovered on January 14, 1997 in the galaxy NGC 1536, SN1997D is the most sub-luminous type II supernova ever recorded. Through an analysis of the light curve and spectra, Turatto et al. [10] suggested that the supernova was a low energy explosion, $\sim 4\times10^{50}$ ergs, of a 26 $M_{\odot}$ star. The observed late-time light curve (up to 416 days after the explosion) is consistent with only $\sim 0.002\ M_{\odot}$ of ^{56}Co in the ejected envelope, much lower than the $\sim 0.1\ M_{\odot}$ typical of most type II supernova (0.075 $M_{\odot}$ in SN1987A). In a preliminary investigation, Zampieri et al. [6] pointed out that the 3 $M_{\odot}$ black hole (prdecited for this model) may emerge in SN1997D as early as ~ 3 years after the explosion, with an accretion luminosity ranging between 10^{35} to as much as 5×10^{36} ergs s^{-1}.

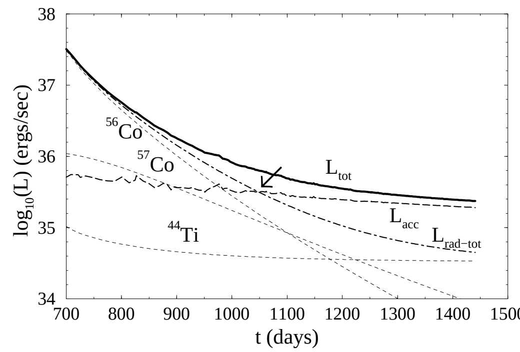
Our calculated light curve for SN1997D based on the best-fit post-explosion model of [10] is shown in Fig. 1. The earlier part of the light curve is in good agreement with the observed data, while at a later time we find that the black hole emerges about 1050 days after the explosion - which corresponds to late 1999 - *NOW!*. Figure 2 compares the heating due to the isotopes ^{56}Co, ^{57}Co and ^{44}Ti to the accretion luminosity. Note that radioactive heating (especially ^{44}Ti) is never negligible with respect to the accretion luminosity, so the total luminosity does not fall off as an exact power law. Nonetheless, the presence of the black hole could still be inferred by attempting to decompose the total light curve.

In this calculation, the total luminosity at emergence is about 7×10^{35}ergs s^{-1}. However, this luminosity is dependent on the finer details of the initial profile, which

FIGURE 1. Light curves including accretion lumninosity for a 35 $M_\odot$ progenitor (model S35A of [9]), the best fit model of [10] for SN1997D (model I), and a variant of SN1997D where the initial conditions allow for a larger late time luminosity (model Ia).

FIGURE 2. The total luminosity of model I for SN1997D and the contributions to the light curve by radioactive heating of ^{56}Co, ^{57}Co and ^{44}Ti, their total ($L_{rad-tot}$), and the accretion luminosity. The arrow marks the time at which $L_{acc} = \frac{1}{2} L_{tot}$.





are difficult to constrain from the early light curve. Considering these uncertainties and those regarding the abundances of ^{57}Co and ^{44}Ti, we find through a revised analytical estimates (which account for γ-ray transparency and Eddington-rate limits on the accretion flow), that while the time of emergence is fairly well determined, the plausible range for the luminosity at emergence is $0.5-2{\times}10^{36}$ ergs s^{-1}. One example, where the luminosity at emergence is $\sim 1.4 \times 10^{36}$ ergs s^{-1} is also shown in Fig. 1. In this case, the accretion luminosity is sufficiently high that contribution of radioactive heating does not cause any significant deviation from a power-law decay. We estimate that such a luminosity is still marginally detectable ($m_v \approx 29$) with the HST STIS camera, so that if observed, SN1997D could provide first direct observational evidence of black hole formation in supernova within the next year.

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